

Reconnaissance survey of coastal boulders in the Moro Gulf (Philippines) using Google Earth imagery: Initial insights into Celebes Sea tsunami events

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Abstract: A recent study has suggested that palaeo-tsunami events in the South China Sea may have attained wave heights of up to 15 m. One method for investigating palaeo-tsunami along coastlines is the study of boulders that, through measurement and the use of hydrodynamic equations, may assist in understanding wave heights. An area with known high magnitude tsunami is the eastern coast of Moro Gulf on the island of Mindanao (Philippines) in the Celebes Sea, where a damaging tsunami of up to 9 m high occurred in 1976. This study undertakes a reconnaissance of the coastline using Google Earth imagery and, appreciating limitations, identifies two potential coastal sites with presumed wave-transported boulders near Namat and Sedem, c. 10 and 55 km from the 1976 earthquake epicentre respectively. Using Google Earth tools, 12 boulders were measured and, with some estimated parameters, heights calculated for both tsunami and storm waves required to transport the boulders. This preliminary analysis indicates that four of the boulders may have been transported by storm activity, but all 12 boulders could have been transported by the 1976 tsunami. Indeed, the orientation of the majority of boulders indicates a flow direction consistent with the location of the 1976 earthquake epicentre. Furthermore, there is no evidence presented in this preliminary analysis to suggest that a tsunami of a magnitude greater than the 1976 event has affected this coastline. An hypothesis is concluded that could be used to guide future fieldwork in this regionally important area of natural hazard studies.

Abstrak: Satu kajian baru-baru ini menunjukkan bahawa peristiwa palaeo-tsunami di Laut China Selatan mungkin telah mencapai ketinggian gelombang sehingga 15 m. Satu kaedah untuk menyiasat palaeo-tsunami di sepanjang garis pantai adalah kajian batu-batan yang, melalui pengukuran dan penggunaan persamaan hidrodinamik, dapat membantu dalam memahami ketinggian gelombang. Kawasan yang pernah dilanda tsunami magnitud yang tinggi adalah pantai timur Teluk Moro di pulau Mindanao (Filipina) di Laut Celebes, di mana tsunami dahsyat setinggi 9 m berlaku pada tahun 1976. Kajian ini melakukan peninjauan garis pantai dengan menggunakan imejan Google Earth dan, peka terhadap ketidakpastian yang wujud, mengenalpasti dua tapak pantai yang berpotensi dengan batu yang berkemungkinan diangkut gelombang berhampiran Namat pada 10 km dan Sedem pada 55 km dari pusat gempa bumi. Dengan menggunakan alat Google Earth, 12 buah batu diukur dan, dengan menganggarkan beberapa parameter, ketinggian dapat dikira untuk kedua-dua gelombang tsunami dan ribut yang diperlukan untuk mengangkut batu tersebut. Analisis pendahuluan ini menunjukkan bahawa empat buah batu mungkin telah diangkut oleh aktiviti ribut, tetapi kesemua 12 buah batu boleh diangkut oleh tsunami tahun 1976. Malah, orientasi majoriti batu menandakan arah aliran yang konsisten dengan lokasi pusat gempa bumi tahun 1976. Selain itu, tiada bukti yang dibentangkan dalam analisis awal ini untuk mencadangkan bahawa tsunami bermagnitud lebih tinggi daripada peristiwa tahun 1976 telah memberi kesan kepada pesisiran pantai ini. Hipotesis yang disimpulkan boleh digunakan sebagai panduan untuk kerja lapangan pada masa hadapan di kawasan kajian alam bahaya yang penting di rantau ini.

Keywords: Tsunami, boulders, coastal geomorphology, Celebes Sea, Philippines, waves

INTRODUCTION

Boulders deposited at coastlines are increasingly considered to be useful in aiding an understanding of marine high energy events and distinguishing between storm or tsunami wave impact along a coastline (e.g. Nott, 1997; 2003; Scheffers *et al.*, 2010; Lorang, 2011; Erdmann *et al.*, 2015). However, the mapping of coastal boulder occurrences is generally limited as such deposits are relatively localised and often mapped in association with erosional coastlines

rather than depositional coastlines. Coastal boulder deposits are most frequently encountered along mid- to high-latitude coasts which have been subjected to glaciation and/or periglaciation, where the erosion of glacial till, for example, releases boulder-sized clasts once the supporting finer sediment matrix has been eroded away. Along sub-tropical and tropical coasts boulder deposits may occur where cliff or rock platform erosion is active, or where relatively steep seaward-facing inland slopes either generate landslides, talus

deposits, or high-velocity streams that deliver coarse clasts to the coast (Haslett, 2016).

Locating physical features in the landscape, such as boulder deposits, for analysis has traditionally been undertaken through field surveys; however, with the advent of freely available tools, such as Google Earth, many studies now make use of this technology in geoscience education (e.g. Haslett *et al.*, 2011) and to undertake rapid reconnaissance work in order to make some preliminary analyses (e.g. Fisher *et al.*, 2012). Google Earth images have been employed here to undertake a reconnaissance for boulder deposits along the eastern Moro Gulf coast on the island of Mindanao in the southern Philippines.

The Philippines have been selected as a study location due to the occurrence of both powerful storms and associated surges, in the form of typhoons, and tsunami that affect both the Philippines and neighbouring countries, such as Malaysia (Raj, 2007). The eastern Moro Gulf coast, in the northern Celebes Sea, has been selected as relatively few typhoons make landfall on Mindanao; between 1945 and 2013 only 10 typhoons out of total of 406 Philippine typhoons made landfall in Mindanao (Takagi & Esteban, 2015). Nevertheless, maximum probable storm water levels of up to 4 m high have been calculated for the eastern Moro Gulf coast (Lapidez *et al.*, 2015), and the area is known to have experienced damaging tsunami of up to 9 m high in 1976 generated by a magnitude 8.1 earthquake offshore Mindanao (Badillo, 1978; Badillo & Astilla, 1978; Weigel, 1980; Løvholt *et al.*, 2012). However, Rogozhin (2016) recently suggests from a palaeo-tsunami study that the South China Sea, in the context of the seismically active zone around the Philippines, may have experienced tsunami up to 15 m high within the past 1000 years. Therefore, it is important to begin to analyse specific coastlines within the region in terms of their tsunami risk. Boulder analysis provides one way in which this may be advanced. The aims of the study are to (1) identify and describe any boulder deposits along the coastline, (2) undertake preliminary

measurements and analysis of any sites, and (3) make preliminary interpretations in relation to known high energy events impacting this coastline with a view to making recommendations for further research in the region.

STUDY AREA AND METHODS

The Moro Gulf is a large embayment on the southern shore of Mindanao island in the Philippines and it opens up into the northern Celebes Sea (Figures 1 and 2). The area is seismically active with the northward subducting Cotabato Trench, movement along which triggered the magnitude (M_w) 8.1 earthquake on 16th August 1976, generating a damaging tsunami up to 9 m high along the coast near Lebak in the Moro Gulf that caused approximately 4000 fatalities (Løvholt *et al.*, 2012).

The Moro Gulf coastline was initially surveyed here using Google Earth Pro imagery at an eye elevation of approximately 3-3.5 km. It must be stated at the outset that limitations undoubtedly exist in using Google Earth imagery and, therefore, results derived from utilising its imagery must be considered as indicative only. Nevertheless, using the tool, the majority of the coast was seen to be low-lying and comprise what appear to be fine-grained sediment beaches, muddy tidal rivers and associated deltaic features often with creek networks lined by mangroves. However, where rocky shores were identified these were examined in more detail at an eye elevation of between approximately 50-350 m.

Where boulder-sized clasts were considered to be present, the presumed boulders were measured using the measuring tool provided by Google Earth; however, only two axes of each boulder could be measured, that is the axes of the boulder up-face presented in the image. From experience, it is assumed that these represent the a and b axes of the boulder, the longest and intermediate axes respectively, with the shorter c axis being perpendicular to the image and, so, unmeasurable. These boulder measurements, along with a general figure for the density of the lithology, an estimate



Figure 1: The region of southeast Asia indicating the location of the 1976 earthquake epicentre in the northeast of the Celebes Sea adjacent to Mindanao (Philippines) (see Figure 2).

for the c axes, and a typical shore slope of 10° , were used in the revised hydrodynamic equations of Haslett & Wong (2019), based on those of Nott (2003) and Nandesena *et al.* (2011), who provide a full explanation of the equations used. These equations estimate the wave height required to transport each boulder under storm (H_{storm}) or tsunami (H_t) conditions for sub-aerial, submerged, and joint-bounded pre-transport settings (see Nott, 2003).

The orientation of the longer a-axis was also measured, as was the general orientation of the shore in the immediate vicinity, using the ruler and compass tool in Google Earth. Boulder orientation may offer some insight into whether the boulders are *in situ* or have been wave transported and, as far as practicable, the criteria of Bryant & Haslett (2007) are also considered (see also Haslett & Bryant, 2007).

As a caveat, it must be noted that, without field verification, the possibility cannot be excluded that the presumed boulders measured in this study may not be boulder clasts and might be another geomorphological feature or, if they are boulders, that they may not have been wave-transported and remain *in situ*. However, the authors consider that there is a high likelihood that the measured features are boulders and that some attributes of

these features, such as gathering into groups, suggests wave transportation for at least some of them.

RESULTS AND DISCUSSION

Two rocky shore sites were identified from the Google Earth survey, both with what appear to be boulder-sized clasts; (1) a southerly extending peninsula at Sedem and (2) the west-facing shore of a headland across the bay from Namat (Figure 3). At Namat (Figure 4), there appear to be three large isolated boulders (boulders 1-3) and two groups of smaller boulders that appear to be accumulated into approximately shore-normal bedforms (boulders 4-6 are measured from these accumulations). At Sedem (Figures 5 and 6), two groups are measured, one at the tip of the headland where the a axes of the boulders appear to be orientated parallel to or ‘wrapped around’ the headland (boulders 11 and 12), and a group N66°W along the shore from the tip of headland which appear to be lying obliquely (boulders 7-10).

The geology of both these locations appear to comprise mainly Tertiary greywacke sandstones with some interbedded shales and other lithologies (CCOP, 2018; MGB, 2018). Therefore, the rocks are likely to be well-



Figure 2: The island of Mindanao (Philippines) and the Moro Gulf. The epicentre of the 1976 earthquake and site of tsunami generation is indicated. See Figure 3.

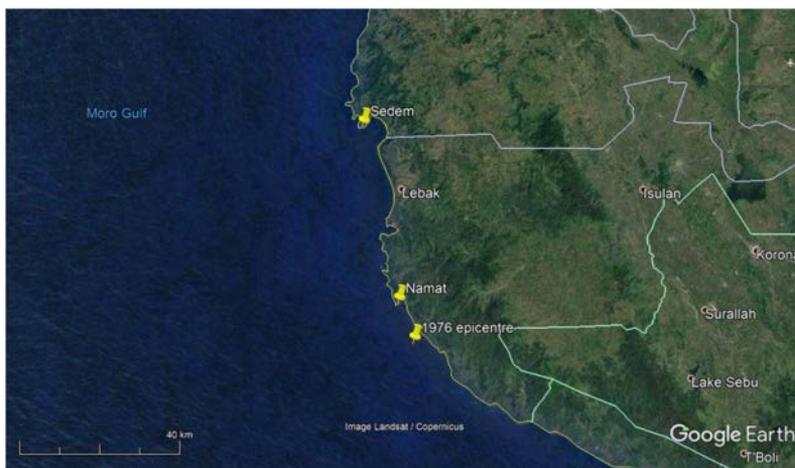


Figure 3: Part of the eastern shore of the Moro Gulf on the island of Mindanao (Philippines), indicating the location of the epicentre of the 1976 earthquake and tsunami generation site, and the two locations where boulders occurrences have been suggested near Namat and Sedem.



Figure 4: Google Earth image of the coast near Namat (see Figure 3) showing boulders deposited along the western shore of the headland. Three large isolated boulders and two groups of smaller, accumulated, boulders are indicated with the arrows. The image was taken on 14th November 2016 and is the view from an eye altitude of 330 m; the location of the centre of the image is 6°22'37.33"N, 124°03'23.55"E.



Figure 5: Google Earth image of the coast near Sedem (see Figure 3). The arrow is indicating the headland with boulders that have been measured for this study. The image was taken on 28th January 2016 and is the view from an eye altitude of 3.39 km; the location of the centre of the image is 6°46'36.51"N, 123°58'49.28"E.



Figure 6: Google Earth image of the headland near Sedem (see Figure 5) showing boulders (arrowed) deposited at the tip of the headland and along the western shore of the headland. The image was taken on 14th February 2013 and is the view from an eye altitude of 90 m.

bedded, possess a density of approximately 2650 kg m^{-3} , and also likely to produce tabular boulders upon erosion. Indeed, field photographs of Tertiary clastic sedimentary rocks elsewhere in the Philippines depict relatively thinly bedded units (Aurelio *et al.*, 2013). Given this assumption, and to permit a preliminary analysis, the c axis value for each measured boulder is perhaps not unreasonably estimated, to provide an approximate minimum likely thickness, as one-third of the b axis. Six boulders were measured at each of the locations, totalling a dataset of 12 boulders, and these data are presented in Table 1. The

calculated wave heights based on the collected boulder data are also presented in Table 2, representing the minimum storm (H_{storm}) and tsunami (H_t) wave height (m) required to move these boulders depending on whether they were in a sub-aerial or submerged setting at the time of wave-entrainment, as a previously detached boulder, or joint bound and quarried and transported by the wave event. The range of wave heights required to move each boulder is plotted in Figure 7 alongside, for comparison, the height of the 1976 tsunami and the maximum storm wave height (4 m).

Table 1: The location, dimensions and a axis orientation of 12 boulders identified and measured in this study (*c axis is estimated).

Location	Boulder number	Latitude	Longitude	a axis (m)	b axis (m)	c axis (m)*	A axis orientation
Namat	1	6°22'39.43"N	124°03'20.49"E	12.84	5.07	1.67	138-318°
	2	6°22'39.04"N	124°03'21.01"E	10.26	5.89	1.94	133-313°
	3	6°22'36.65"N	124°03'22.91"E	12.39	5.66	1.87	148-328°
	4	6°22'38.65"N	124°03'21.42"E	4.59	4.44	1.47	60-240°E
	5	6°22'38.03"N	124°03'22.07"E	5.11	4.47	1.48	59-239°
	6	6°22'38.11"N	124°03'22.39"E	4.04	2.74	0.90	60-240°
Sedem	7	6°46'04.76"N	123°58'32.46"E	4.17	1.61	0.53	78-258°
	8	6°46'04.92"N	123°58'32.64"E	2.42	1.14	0.38	57-237°
	9	6°46'04.87"N	123°58'32.67"E	2.98	1.10	0.36	56-236°
	10	6°46'04.81"N	123°58'32.71"E	4.81	1.41	0.47	62-242°
	11	6°46'04.39"N	123°58'33.40"E	4.01	1.89	0.62	101-281°
	12	6°46'04.41"N	123°58'33.64"E	2.45	1.30	0.43	62-242°

Table 2: Calculated storm (H_{storm}) and tsunami (H_t) wave heights and flow velocity (u) derived from hydrodynamic equations, using data in Table 1, for the three pre-transport settings of Nott (2003).

Pre-transport settings									
No.	Submerged			Sub-aerial			Joint bounded		
	Tsunami (H_t) (m)	Velocity (u) (m/s)	Storm (H_{storm}) (m)	Tsunami (H_t) (m)	Velocity (u) (m/s)	Storm (H_{storm}) (m)	Tsunami (H_t) (m)	Velocity (u) (m/s)	Storm (H_{storm}) (m)
1	4.51	13.30	18.05	3.16	9.31	12.64	8.31	18.05	33.24
2	5.24	14.34	20.97	3.67	10.04	14.68	9.65	19.45	38.61
3	5.04	14.05	20.15	3.53	9.84	14.11	9.28	19.07	37.10
4	3.95	12.45	15.81	2.77	8.71	11.07	7.28	16.89	29.11
5	3.98	12.49	15.92	2.79	8.74	11.14	7.33	16.95	29.30
6	2.44	9.78	9.76	1.71	6.84	6.83	4.49	13.27	17.96
7	1.43	7.50	5.73	1.00	5.25	4.01	2.64	10.17	10.55
8	1.01	6.31	4.06	0.71	4.42	2.84	1.87	8.56	7.47
9	0.98	6.20	3.92	0.69	4.34	2.74	1.80	8.41	7.21
10	1.26	7.01	5.02	0.88	4.91	3.51	2.31	9.52	9.24
11	1.68	8.12	6.73	1.18	5.68	4.71	3.10	11.02	12.39
12	1.16	6.74	4.63	0.81	4.71	3.24	2.13	9.14	8.52

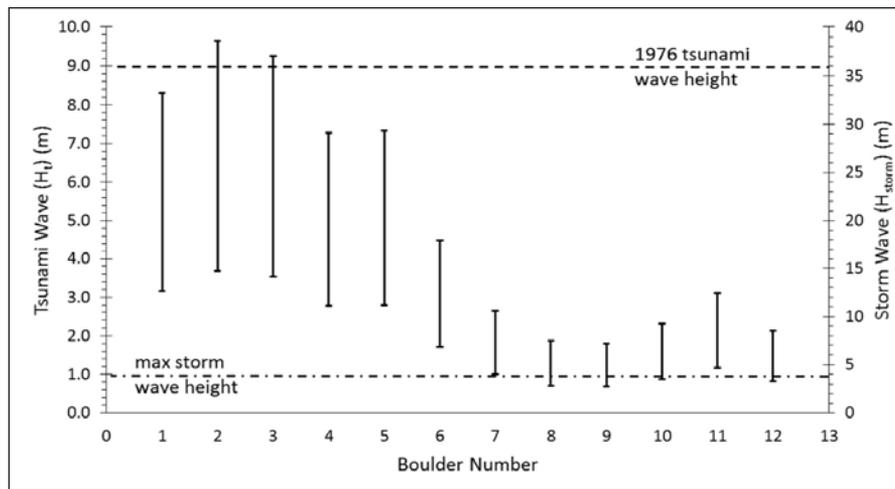


Figure 7: Plot of calculated wave heights ranges from Table 2 for tsunami (H_t) and storm (H_{storm}) waves for each of the boulders (1-12) measured in this study near Namat (boulders 1-6) and Sedem (boulders 7-12). The maximum storm and tsunami wave heights known to have been experienced along this coast are shown for comparison, plotted on the respective axis.

Of the 12 boulders analysed, four of them (boulders 8, 9, 10 and 12), from the Sedem site, may have been transported by storm wave activity, but only if they were previously detached in a sub-aerial pre-transport setting or, in the case of boulder 9 only, as a boulder in a submerged setting. However, all boulders measured, both at Sedem and Namat, could have been transported and deposited by the 1976 tsunami under most pre-transport settings.

With regard to the orientation of the axis of the measured boulders, it is generally accepted that boulders will, if conditions are suitable, become re-oriented normal to the flow direction. The majority of boulders measured (nos. 4-10 and 12) possess an axis orientation that suggests a flow direction from 146°SE - 168°SSE , which points towards the epicentre of the 1976 earthquake and tsunami generation site at $6^\circ17'24''\text{N}$, $124^\circ5'24''\text{E}$ (Geohack, 2018), a bearing of 159° and c. 10.3 km from Namat, and 166° and c. 54.1 km from Sedem. Therefore, the 1976 tsunami would appear to be a likely candidate for the transport and deposition of the majority of the boulders studied here. At Namat, however, three large and isolated boulders (1-3), each exceeding 500 tonnes, possess an axis orientation that is parallel to the coastline (Figure 4). It is not possible to confirm from the Google Earth images whether these boulders have been wave-transported at this location, or to what extent, but they clearly have not been orientated relative to the 1976 tsunami as might have been expected from numerical modelling (Imamura *et al.*, 2008). Although a field survey would be required to investigate these boulders further, it appears from this preliminary analysis that these boulders do not necessarily indicate that a wave event of a magnitude higher than the 1976 event has affected this coastline. Furthermore, boulders 11 and 12 at Namat, which appear to wrap around the headland, may be due to refraction of the tsunami around

the headland, which might also explain the outlying axis orientation of boulder 11.

Taken together, this preliminary analysis suggests that the boulder occurrences identified here through the use of Google Earth imagery might be adequately explained in relation to the 1976 tsunami event that affected this coastline. With regards to Rogozhin's (2016) assertion that palaeo-tsunami may have been experienced in the South China Sea of up to 15 m high within the past 1000 years, no evidence has been gathered here to suggest that tsunami greater than 9 m high have been experienced along the coast of the Moro Gulf. This may not be surprising as Okal *et al.* (2011) suggest that the South China Sea and adjoining seas are "largely independent basins where tsunamis generated in one basin do not leak into another" (p. 1153). However, clearly, this suggestion requires careful evaluation through future field studies as, for example, changes to boulder axis measurements will affect the results.

CONCLUSIONS

From these preliminary data presented here, which are based upon a reconnaissance exercise of the Moro Gulf coast of Mindanao using Google Earth imagery, and notwithstanding any limitations of the imagery and field verification of the boulder clasts, some conclusions may be usefully established in the form of a hypothesis that warrants being tested through field investigation:

1. That boulders appear scarce along the coast of the Moro Gulf, but two accumulations seem to occur at headland locations near Namat and Sedem;
2. That the dimensions of these presumed boulders may be measured and used in hydrodynamic equations to establish the storm (H_{storm}) and tsunami (H_t) wave heights required to transport these boulders (albeit the

c axis is not measurable using Google Earth imagery and has, therefore, been estimated here to permit a preliminary analysis, but could be measured in the field);

3. The returned wave heights indicate that whilst some boulders may be transported by known storm events, all of the boulders may have been transported by the 1976 tsunami event that affected this coastline;
4. The orientation of the majority of boulders indicate a flow direction for transportation consistent with the location of the epicentre of the 1976 earthquake that generated the tsunami;
5. That from the measurements of boulders analysed here there is no evidence to suggest that a tsunami of a magnitude greater than that of the 1976 event has affected this coastline.

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